Higgs Alignment from Extended Supersymmetry

Sophie Williamson

LPTHE, Université Paris 6, CNRS

In collaboration with Karim Benakli and Mark D. Goodsell

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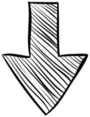
Motivation

- Absence of strongly-coupled particles at the LHC $\rightarrow$ interest in new electroweak-coupling particles.
- Is the Higgs boson part of a larger scalar sector?
- Strong LHC constraints imply the heavy Higgs should be aligned with or decoupled from the SM-like one.
- Interested in theories where alignment is untuned.
- Could finding a second Higgs doublet unveil a full SUSY theory?

Higgs Alignment

- In minimal SUSY: Two complex $SU(2)$ Higgs doublets - $\mathbf{H_u}$, $\mathbf{H_d} \xrightarrow{\text{EWSB}}$ 5 physical Higgs bosons: h, H, A, $H^{\pm}$.
- However: strong contraints on Higgs couplings from experiment.



- *Higgs Alignment*: Mass eigenstates align with the VEV $\rightarrow$ SM-like Higgs.
- Can be realised naturally through an $\mathcal{N} = 2$ supersymmetry.

$\mathcal{N} = 2$ Supersymmetry in a Dirac Gaugino model

- But isn't the matter sector fundamentally chiral and $\therefore \mathcal{N} = 1$?

  $\rightarrow$ Assume $\mathcal{N} = 2$ supersymmetry in the Higgs/gauge sector only.

  The Dirac gaugino model (MDGSSM).

- 2 Higgs doublets of MSSM naturally sit in an $\mathcal{N} = 2$ hypermultiplet.
- $\mathcal{N} = 2$ extended gauge sector:
  - Add $\mathcal{N} = 1$ chiral multiplets **S** (singlet), **T** ($SU(2)$ triplet), **O** ($SU(3)$ octet) in the adjoint representation of the corresponding gauge groups.
  - Majorana gauginos $\rightarrow$ Dirac gauginos

Modifications to the Higgs sector

- Choose $\mathcal{N} = 2$ conserving superpotential.
- Modification to the MSSM Higgs sector:

$$W_{\text{Higgs}} = \mu\, \mathbf{H_u} \cdot \mathbf{H_d} + \lambda_S \mathbf{S}\, \mathbf{H_u} \cdot \mathbf{H_d} + 2\lambda_T\, \mathbf{H_d} \cdot \mathbf{T} \mathbf{H_u}$$

- At tree level:
  $\mathcal{N} = 2$ supersymmetry imposes:

$$\lambda_S = \frac{g'}{\sqrt{2}}\,, \qquad \lambda_T = \frac{g}{\sqrt{2}}\,,$$

The Two-Higgs Doublet Model Limit

Alignment basis:

- Mass matrices for the CP-even scalars:

$$\mathcal{M}_h^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & m_A^2 + Z_5 v^2 \end{pmatrix} \qquad \text{with } Z_i = Z_i(\lambda_i).$$

- Alignment when $Z_6 \to 0$.

With $\mathcal{N} = 2$ supersymmetry, at tree level:

$$m_h^{N=2} = m_Z \,, \qquad m_H^{N=2} = m_A$$

$\rightarrow$ Alignment for any value of $\tan\beta$!

- First demonstrated by Antoniadis, Benakli, Delgado and Quirós in the context of gauge mediation.
- Pheno. study done by Ellis, Quevillon, Sanz taking $M_{\mathcal{N}=2} = Q$.

Misalignment: $\mathcal{N} = 2$ to $\mathcal{N} = 1$ SUSY

Radiative Corrections: Chiral Matter

- Chiral fields present at the $\mathcal{N} = 2$ scale.
- Splitting of λ_S, λ_T from their $\mathcal{N} = 2$ scale values during running:

$$Z_6(M_{SUSY}) = \frac{1}{4} s_{2\beta} c_{2\beta} \left[(2\lambda_S^2 - g_Y^2) + (2\lambda_T^2 - g_2^2) \right] + \text{threshold corrections.}$$

Misalignment: $\mathcal{N} = 1$ to $\mathcal{N} = 0$

Radiative Corrections: Mass splitting

- Mass splitting between the fermionic/bosonic components of the superpartners:

$$Z_6(v) \simeq Z_6(M_{SUSY}) + s_\beta^3 c_\beta \times \frac{3y_t^4}{8\pi^2} \log \frac{m_{\tilde{t}}^2}{m_t^2}$$

- Less misalignment than in the MSSM:
  - No tree-level contribution to Z_6.
  - Stop correction to m_h smaller in the MDGSSM.
    $\rightarrow \mathcal{O}(\frac{1}{2})$ for $\tan\beta = 2$ because of:
    - Tree-level boost to m_h (so smaller stop contributions required)
    - Only small stop mixing is possible

Precision Study: Implementation

$Q \to M_{SUSY}$

- 1l matching Yukawas to SM values; gauge threshold corrections.
- 2l corrections to m_h.
- Running: 2l Low energy THDM + Dirac electroweakinos in SARAH.

$M_{SUSY} \to M_{\mathcal{N}=2}$

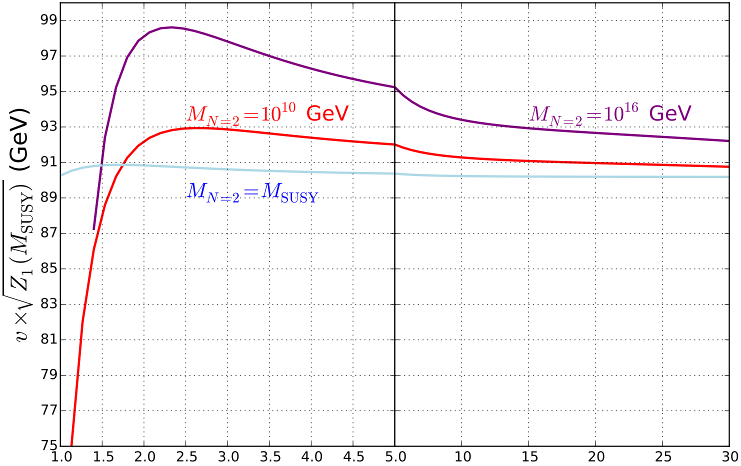
- Tree-level corrections from DG-masses and 1l corrections to λ_i.
- Conversion of $\overline{MS} \to \overline{DS}$ gauge + Yukawa couplings.
- Running: 2l MDGSSM in SARAH.

Assumptions

- $Q = 400$ GeV.
- M_{SUSY}: Stop masses; other MSSM particles $\to$ vary to obtain $m_h = 125$ GeV at 2l.

Precision Study: Results I

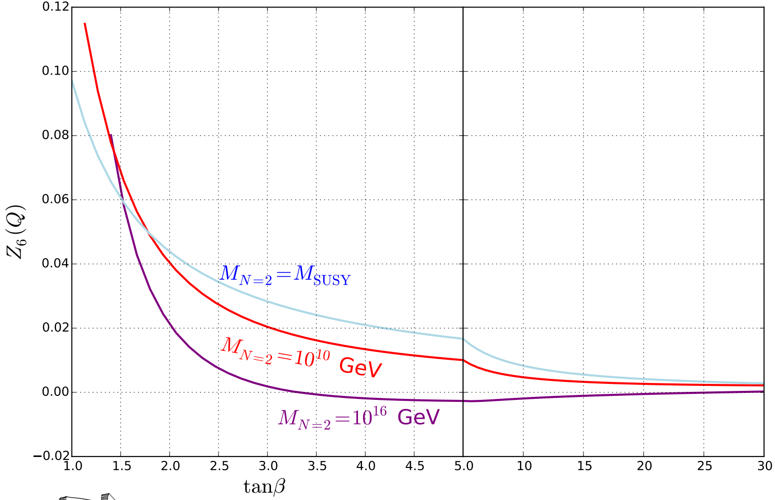
Tree level m_h before running $M_{SUSY} \to Q$.



- Increasing $M_{\mathcal{N}=2}$ increases m_h.
- MSSM: m_h^{tree} goes like $m_Z|\cos\beta| \to$ drops off for small $\tan\beta$.

Precision Study: Results II

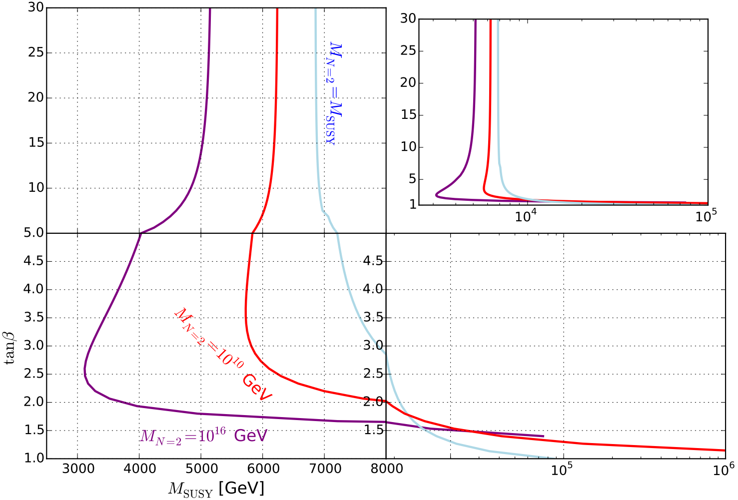
Alignment in the Dirac Gaugino Model



⇨ Independent of m_A, m_h is very SM-like for $\tan\beta \geq 3$.

Precision Study: Results III

Higgs mass bounds on the SUSY scale



- Minimum for M_{SUSY} around $\tan\beta \in (2, 3)$.

Experimental Constraints

Higgs couplings

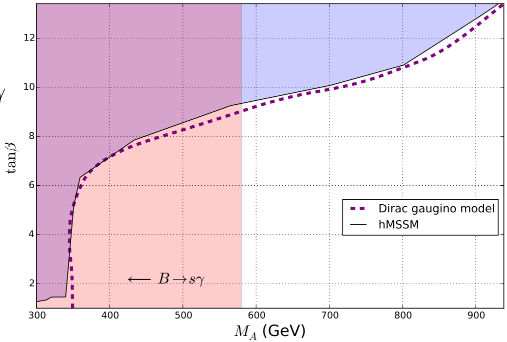
- Model realises excellent alignment $\rightarrow$ no significant constraint from Higgs couplings.

Electroweak precision corrections

- Current bound: $\Delta\rho = (3.7 \pm 2.3) \times 10^{-4}$ $\rightarrow$ central value restricts $m_{T_+} > 2$ TeV.

Flavour

- Strongest constraint: B $\rightarrow$ sγ



Conclusions

- Alignment is realised naturally in $\mathcal{M}_h$, and preserved by quantum corrections.
- The splitting of λ_S and λ_T from the $\mathcal{N} = 2$ relations
  - Boosts m_h
  - Lowers M_{SUSY}
  - Improves alignment
- M_{SUSY} could be as low as 3 TeV.

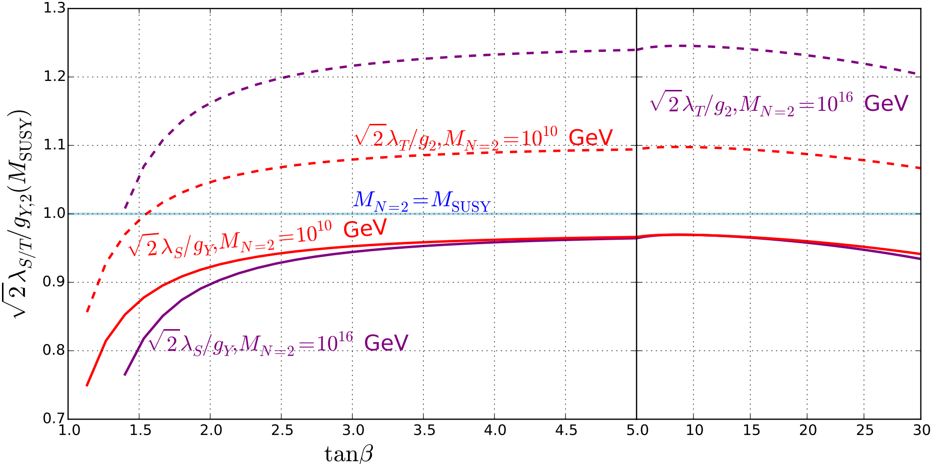
Backup slides I

The precision study implemented scans over $\tan\beta$, M_{SUSY} and $M_{\mathcal{N}=2}$ and defined

- $M_{scalars}$ (heavier $S,\ T$ scalars) $= 5$ TeV.
- $(m_{DY}, m_{D2}, \mu) = (400, 500, 600)$ GeV.
- $m_A^{tree} = 600$ GeV.
  - $m_A^{tree} \sim m_H \sim m_{H^\pm}$ because of small mixing.

Backup slides II

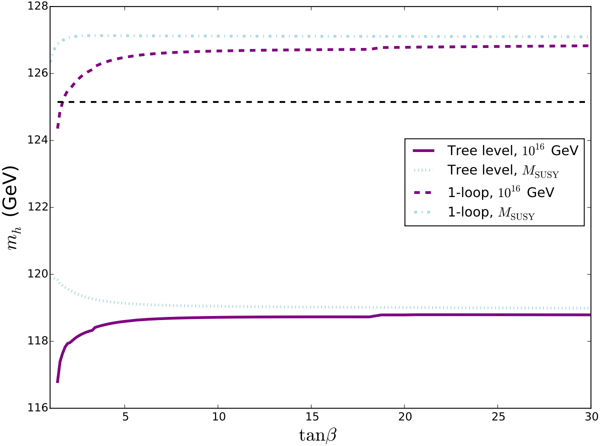
The dependence of the couplings on the $\mathcal{N} = 2$ scale.



$\rightarrow$ Enhancement of m_h due to λ_T splitting.

Backup slides III

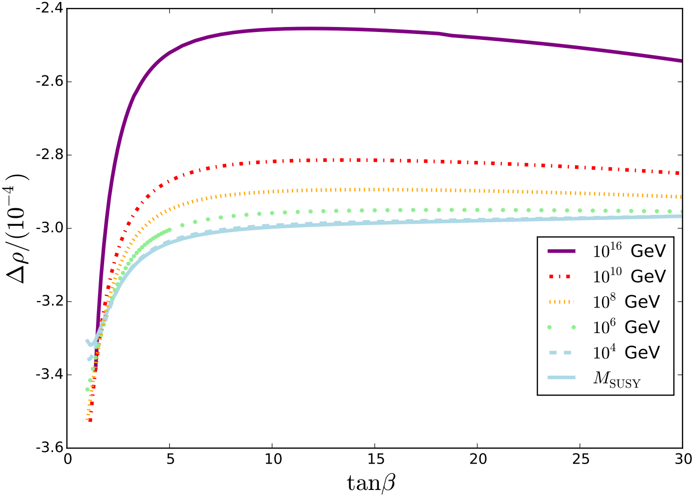
Effects of loop corrections in the low-energy theory on m_h.



$\rightarrow$ Loop effects from tops, heavy Higgses and electroweakinos boost m_h by $\sim$ 5 GeV.

Backup slides IV

$\Delta\rho$ at 1l in the low energy theory:



$\rightarrow$ Always well within experimental bounds.